Microgravity Test of Universality and Scaling Theory Predictions near the Liquid-Gas Critical Point of ^{3}He

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We are developing an experimental system capable of the simultaneous measurement of several static and dynamic critical exponents near the ^{3}He liquid-gas critical point. The significant reduction of gravity effects associated with a microgravity experiment should permit a more accurate determination of the static critical exponents, α and γ, and thus provide a more stringent test of the Renormalization Group Theory predictions. At this time a cryostat is being constructed for high resolution measurements of temperature ($1:10^9$), pressure ($1:10^{11}$), and density ($1:10^7$). Progress on the design and fabrication of the cryostat and experimental cell is presented. Also, issues that are important to the experiment and require further research are discussed.

Introduction

Large gravity induced density gradients present in ground-based experiments prevent an unambiguous test of universality and scaling theory predictions near the liquid-gas critical point. Ground-based measurements were previously performed in experimental cells of small vertical height to minimize gravity effects. Unfortunately the gravity affected region for most measurements begins in the reduced temperature range $5\text{x}10^{-5}$ - $5\text{x}10^{-4}$. Thus, most ground-based experiments have only a limited range of reduced temperatures to test scaling theory predictions. This is the motivation for performing microgravity experiments near the liquid-gas critical point. Calculations show that a microgravity environment could provide measurements up to an additional two decades in reduced temperature closer to the phase transition. The ^{3}He critical point was chosen because (a) most of the diverging thermodynamic parameters have been measured in one-g, (b) quantum effects that may affect critical behavior are strongest in ^{3}He, and (c) the high precision temperature measurement capability developed for the Lambda Point Experiment can be applied to the ^{3}He critical point. We plan to determine the critical exponent, α, by measuring the adiabatic sound velocity and the constant volume specific heat along the critical isochore. The temperature, density, and pressure will also be measured to determine the isothermal compressibility and obtain the critical exponent, γ. The sound attenuation and dispersion will be measured to test dynamic scaling predictions.

Important Issues

There are several important issues that we need to investigate and resolve before a flight proposal can be planned. First there is the question of how close we can approach the critical point before various phenomena will smear out the transition. Vibrations of the experimental apparatus could limit the closest approach to the critical point. We are now evaluating the effect of this g-jitter on our proposed experiments near the ^{3}He critical point. Our progress on this study is presented in another paper in this workshop [1].

We also need to measure the temperature with high resolution. This requires a thermometer like the Copper Ammonium Bromide (CAB) HRT's developed by the Stanford group for their lambda point studies. Unfortunately, these CAB thermometers are not sensitive enough at the ^3He critical point that occurs at 3.3 K. We are now in the process of evaluating a $GdCl_3$ thermometer for use at 3.3 K. The results from the first measurements of the sensitivity and noise of this $GdCl_3$ thermometer are presented in another paper in this workshop [2].

In our planned experiments the most difficult parameter to measure near the critical point is the isothermal compressibility. This quantity is determined from the ratio of the change in the density to the change in the pressure at constant temperature. We plan to fill the measurement cell to the critical density and then produce density changes by adjusting the cell volume. Our calculations show that a density change of the order of 1% can be attained with high precision using deflections of a flexible superconducting membrane in a magnetic field. Because the compressibility of the fluid diverges strongly, a constant change in density will lead to smaller and smaller changes in the pressure as the critical point is approached.

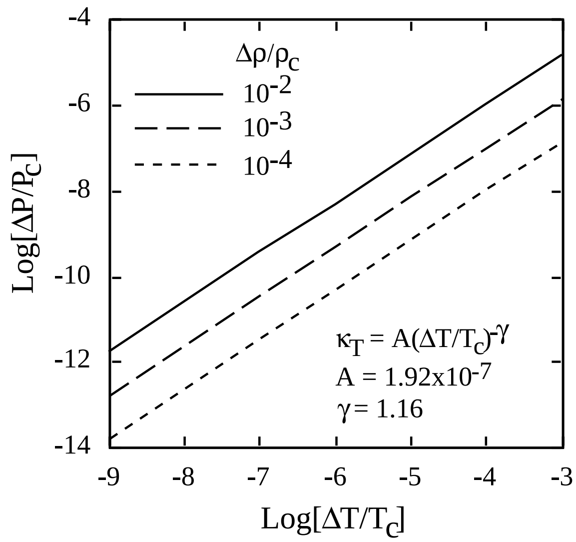

Fig. 1. Reduced pressure verses reduced temperature for fixed reduced densities.

To attain a reduced temperature of 10^{-7} we will need to resolve pressure changes to $1:10^{11}$. This problem is illustrated in Fig.1. Here we show the reduced pressure verses reduced temperature near the critical point for a set of reduced densities. For this analysis, we used the compressibility coefficients obtained by Behinger *et al*. along the critical isochore [3]. We see for example, that for a 1% density change, shown by the solid line, a reduced temperature of 10^{-7} leads to a pressure change of less than 10^{-9}. Furthermore, if we want 1% accuracy, we will need to measure pressure to at least $1:10^{11}$. If we make smaller density changes the ability to measure pressure changes becomes even more difficult. At this time we are collaborating with Rob Duncan to evaluate his SQUID based pressure transducer for measuring small pressure changes. Calculations show that this design should be capable of measuring pressure changes of approximately $1:10^{11}$ [4].

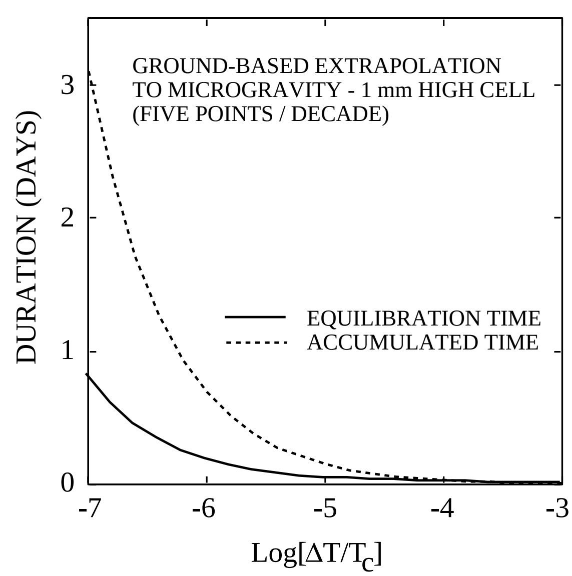

Fig. 2. Expected equilibrium time constant for measurements near the ^3He critical point.

One of the major problems for measurements very near the critical point is the long equilibration times that are required for density fluctuations to relax. These relaxation times are long because the thermal diffusivity approaches zero as the critical point is approached. This problem is also present in a microgravity environment and thus a rather long duration space flight will be require. We plan on using a cell that has a 1 mm height to minimize the time constant associated with density fluctuations. We have estimated the time it would take to perform a sweep through the critical region. This result is shown in Fig. 2. Here, we extrapolated the equilibration time constant for density relaxation near the ^{3}He critical point recently obtained by Horst Meyer's group [5] to our expected situation. The solid curve is the expected equilibration time as a function of the reduced temperature. Assuming five equilibrium points per each decade of reduced temperature, we show with the dashed line the accumulated time required to perform measurements to a reduced temperature of 10^{-7}. We see that even for this minimal data taking scenario, it would take approximately 3 days to perform this sweep. By assuming the need for at least five to ten sweeps and including the time to take data we arrive at a total mission time of more than 30 days.

While we can plan for this long duration flight time, we feel it may be time to rethink the way that temperature changes (and the resultant density stratifications) are produced very near the critical point. The conventional method is to heat the container walls and wait for equilibrium through heat transfer into the fluid. Since very near the critical point, we require small amounts of heat to produce small temperature changes, there may be other heating techniques that can be used that could uniformly heat the entire fluid volume. For example, one possibility is some form of electromagnetic radiation that has a large penetration depth in the fluid and thus will be absorbed uniformly within the sample. Another possibility is to use an energy absorbing mechanism associated with a spin system. In the case of ^{3}He, there is a nuclear susceptibility that may be used to absorb energy. We plan to take a closer look at these types of energy absorbing mechanisms as a possible alternative approach to heating the sample.

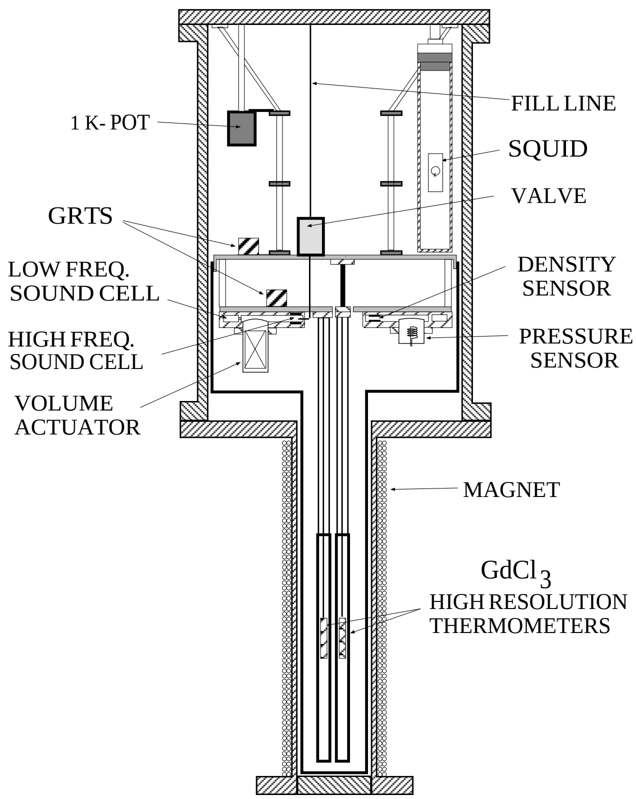

Fig. 3. Schematic of lower portion of cryostat.

Cryostat and Experimental Cell

Figure 3 is a schematic of the lower portion of our cryostat. It is similar to the systems developed by the Stanford group in their studies of the Lambda Point. This system has four isothermal stages with the last stage supporting our experimental cell. The last two stages are temperature controlled using $GdCl_3$ high resolution thermometers. Details of the thermometers are described in ref. [2]. The critical point cell will be filled using a low temperature valve that we are developing.

The planned design of our critical point cell is shown in Fig. 4. The fluid volume will be situated in a cylindrical annulus 1 mm high.

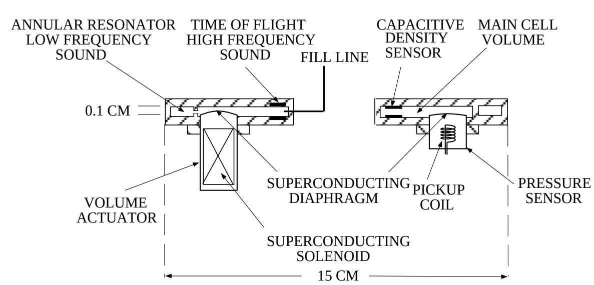

Fig. 4. Schematic of proposed ^{3}He critical point cell.

The outermost region is an annular resonator for measuring low frequency sound velocity and attenuation. There will also be sound transducers imbedded in the cavity walls for measuring high frequency sound properties. A superconducting flexible diaphragm and a solenoid will be used as a volume actuator. The fields produced by the solenoid will adjust the deflection of a superconducting Nb diaphragm. Capacitive measurements will continuously monitor the actual density changes using the Clausius-Mossotti relation. The pressure in the cell will be measured by a pressure sensor consisting of another superconducting diaphragm, whose deflection will be monitored by a SQUID pickup coil.

Conclusions

We plan to complete the construction of the cryostat within the next several months and then evaluate a SQUID based pressure transducer and magnetic volume actuator in collaboration with Rob Duncan. The ^{3}He critical point cell will then be fabricated and ground-based experiments will be performed to within a reduced temperature of approximately 10^{-7}. The final task of this program will be to optimize the experimental procedures to minimize the time to perform all the required measurements.

Acknowledgments

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References

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